REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	12 June, 1995	Final Technical, 3/3/92-3/2/95

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Thin Magnetic Films	AF/FA9620-92-J-0185 61102F 2305-GS
6. AUTHOR(S) E. D. Dahlberg	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Physics, University of Minnesota 116 Church St. SE Minneapolis, Minnesota 55455	8. PERFORMING ORGANIZATION REPORT NUMBER AFOSR-TR-95-0446
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE Bolling AFB Washington, D.C. 20332-6448	10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-92-J-0185
11. SUPPLEMENTARY NOTES	DTIC ELECTE JUN 28 1995 S F D
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This research involved studies of the magnetic properties of multilayered magnetic films and high quality thin films. Both ultra high vacuum sputtering and molecular beam epitaxy techniques were utilized to prepare the films. Both electrical transport and mageto-optic effects were use to measure the magnetic properties of the films and multilayers. The physics of the Giant Magnetoresistance (GMR) and multilayer exchange coupling was investigated by precise measurements of the GMR in both anisotropic magnetoresistance states. The effect of ion implanting, to cause point defects in the layers, was used to modify both the coupling between the layers and the GMR.

19950627 014

14. SUBJECT TERMS	15. NUMBER OF PAGES
	10 (includes this)
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

FINAL TECHNICAL REPORT FOR
AFOSR GRANT NO. AF/FA9620-92-J-0185

SUBMITTED TO
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AFB, DC 20332-6448

Grant Title: Thin Magnetic Films

Starting Date: 3 March, 1992

Report Date: 8 June, 1995

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Accesion For	
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I. Statement of Work

This research program was directed at developing new models for a more fundamental understanding of magnetism and to investigate new magnetic phenomena such as the recent discovery of exchange coupled multilayers. The research focused on the use of advanced thin film preparation techniques to prepare high quality multilayered and single layer thin films. Much of the research utilized magneto-transport techniques to probe the magnetic properties of the magnetic films. In particular, the research has investigated the magnetic properties of bcc Co, the role of interfacial disorder in the recently discovered exchange coupling in magnetic multilayers and the giant magnetoresistance phenomena, the magnetization process and related dynamics in high quality films and a continuing investigation of the temperature dependence of the anisotropy energies in epitaxial iron films. The experimental investigative tools include magnetotransport in magnetic fields up to 10 Tesla, SQUID magnetometry, and magneto-optic magnetometry used for simultaneous detection of magnetization parallel and perpendicular to the applied magnetic fields.

II. Accomplished Research

During this grant, five graduate students received their Ph.D.'s. As a mechanism of describing this research, we will list and discuss the publications which have been either published, submitted for publication, or are currently in draft form.

A. "Magnetization Reversal in (100) Fe Thin Films," Jeffery M. Florczak and E. Dan Dahlberg, Phys. Rev. 44, 9338 (1991).

This publication utilizes the technique we developed using magneto-optics to provide a simultaneous measure of the magnetization in two orthogonal directions in a magnetic film. This work focuses on (100) oriented iron films. These films differ from those we investigated earlier in that they do not possess all three primary three crystallographic directions in the film planes but instead only have the <100> and the <110> directions. The lack of the <111> direction completely alters the magnetization process. The (100) films appear to magnetize in a much more uniform manner. The data taken on these films was modeled with a uniform rotation of the magnetization direction. In the modeling, we were able to determine the anisotropy energies and, as expected, show that prior to a jump in the magnetization direction that the magnetization process is dominated by wall formation.

B. "Comparison of the Spin Valve Effect and the Anisotropic Magnetoresistance in Co/Cu Multilayered Films," Youjun Chen, J.M. Florczak, and E. Dan Dahlberg, J. Magn. Magn. Mater. 104-107, 1907 (1992).

Of current interest in the physics community is the recently discovered giant magnetoresistance (GMR) effect and the long range coupling (LRC) in magnetic/nonmagnetic multilayers. At the present time, a phenomenological model exists for the GMR (using the same physics as for the Stern-Gerlach experiment using spin projection) but a detailed understanding is lacking. This paper which we submitted to the ICM compares the GMR to the anisotropic magnetoresistance (AMR) in systems which exhibit the GMR. We have analyzed the data with a model of Fert which first was used to describe the AMR as a two-current system and in different limits, the GMR. The result of

the work is that the AMR and the GMR are BOTH consistent with this two current model of Fert.

C. "Magnetization Reversal in Fe/GaAs (100) Thin Films," J.M. Florczak and E. Dan Dahlberg, , J. Magn. Magn. Mater. 104-107, 339 (1992).

We are continuing to pursue an understanding of the magnetization processes in thin films; this work is a continuation of that effort. In this work, the angular dependence of the magnetization process in Fe/GaAs (100) thin films was studied using the magneto-optical Kerr effects. The actual experiments relied upon the simultaneous measurements of the magnetization both parallel and perpendicular to the applied field using the technique we pioneered and reported on previously (Florczak and Dahlberg, J. Appl. Phys. 67, 7520 (1990). In the present work, we find the magnetization proceeds in two steps which require the nucleation of 90 domain walls in the films. The interesting point is that there is an angular dependence to the second nucleation process but, within experimental error, not the second. At the present we don't understand this phenomena but are attempting model using the model developed in C. above and a nucleation model of Arrott.

D. "Transport in Co/Ag Multilayered Films," Youjun Chen, P. Rider, E. Dan Dahlberg, E.E. Fullerton, and Ivan K. Schuller, manuscript in preparation.

In this work, we have used two models to understand the transport in multilayered systems; the parallel resistor model and the alloy model. In H. above only the parallel resistor model was used. In this work, both the parallel resistor model and the alloy model were used to describe the transport properties of these films. Again, as in H., the result is that the simple models are lacking and measures of the AMR and the resistivity do not provide sufficient information to improve the models, i.e., we are left with too many adjustable parameters. We do not mean to trivialize the research in H. and I. as they both are necessary as first steps in this exciting research area and both provide direction for the future work which is described below.

E. "Thickness Dependence of the Anisotropic Magnetoresistance in Epitaxial Iron Films," by M. Tondra, E. Dan Dahlberg, and G.A. Prinz, J. Appl. Phys. 73, 6393 (1993).

In this work we determine the value of the anisotropic magnetoresistance (AMR) as a function temperature for the principal crystallographic directions, the (100), (110), and (111), in epitaxial iron films. Averages of the AMR along the different directions is equivalent to the value measured in polycrystalline samples. It is found that for the current applied along the (100) directions in the films with thicknesses over 17.5 nm, it is difficult to saturate the AMR. The reason for this lack of saturation is undetermined. From measurements of the magnetization, this large magnetoresistance can only be associated with a very small percentage of the magnetization of the films, on the order of one percent. One possibility is that for the thicker films, pinning of the magnetization at the interface creates a domain wall and there is a giant magnetoresistance phenomena associated with the wall. For the other directions it is likely that the current is parallel or nearly parallel to the wall and so this behavior does not occur.

F. "A Method of Separating the Giant Magnetoresistance and the Anisotropic Magnetoresistance in Multilayers," by Y-J. Chen, B.H. Miller, and E. Dan Dahlberg, J. Appl. Phys. 73, 6384 (1993).

A number of workers have measured giant magnetoresistance (GMR) samples with rather low values of the GMR. An accurate determination of the GMR in these samples requires one to separate the anisotropic magnetoresistance (AMR) contribution from the measured magnetotransport properties. In this work, we develop a technique which accurately separates the AMR and the GMR in measurements. This technique is applicable for the case where the AMR is unaffected by the GMR scattering phenomena or, at least, in the case of small GMR. The general applicability of this technique will be determined by a detailed understanding of the high resistance GMR state.

G. "Dependence of the Anisotropic Magnetoresistance on Aspect Ratio in Cobalt Films," by Mark Tondra, Brad Miller, and E. Dan Dahlberg, abstract submitted for consideration of publication.(a paper which obtained similar findings was published shortly after we submitted this work and we felt it appropriate to withdraw this from further consideration).

The anisotropic magnetoresistance (AMR) is defined as the asymmetry in the electrical transport with the current parallel and perpendicular to the magnetization of the sample. This work shows that in large area samples, say a square for instance, with inline contacts, the measured AMR is less than the intrinsic AMR of the material. Essentially what occurs is that at the injection point for the current, the current spreads to fill the space available to minimize the current density. This means that the current does not flow exactly parallel to the line of contacts but has components perpendicular also. As the width of the sample increases with fixed contact separation the measured AMR decreases. At fixed width, the measured AMR decreases as the distance between the like polarity (either positive or negative) current and voltage contacts is reduced. This work impacts both basic research designs and device work. In particular, it shows that for experiments on the spin valve effect (SVE), that large square samples with either contacts in the corners or inline contacts reduce any potential error in the SVE determination arising from the AMR; the SVE is an isotropic magnetoresistance phenomena and is thus unaffected by the aspect ratio of the sample other than the conventional geometrical factors.

H. "Magnetization Reversal in CoFe/Ag/Fe/ZnSe Thin Layer Sandwiches," D. Bilic, E. Dan Dahlberg, A. Chaiken, C. Gutierrez, P. Lubitz, J.J. Krebs, M.Z. Harford, and G.A. Prinz, J. Appl. Phys 75, 7073 (1994).

In recent work the spin valve effect (SVE) was measured in Co_xFe_{1-x}/Ag/Fe ($x < 0.7$) thin layer sandwiches grown by molecular beam epitaxy. The field dependence of the SVE was correlated with VSM magnetization data taken on the samples. It was found that only at low fields was there a correlation between the SVE resistance and the magnetization data. These results indicated a more complex reversal mechanism which included substantial magnetizations in directions not measured in traditional VSM measurements. In order to more accurately determine the field dependent magnetization of the samples during reversal, the longitudinal and transverse Kerr effects were measured on the layers. The particular geometry used to measure the Kerr effects was for the light scattering plane to be perpendicular to the applied magnetic field. The transverse Kerr effect data, which in this geometry are sensitive to the magnetization parallel to the applied magnetic field, replicated the VSM data. The longitudinal Kerr effect, which is sensitive to the net magnetization perpendicular to the applied field (in the plane of the film), indicated a substantial perpendicular magnetization component. Based upon previous work on epitaxial iron films[2,3,4], it appears that the magnetization

reversal process proceeds by transitions between easy axes. From these measurements, the anomalous resistances observed as a function of the applied magnetic field in[1] are explained by having one of the films soft, and two easy axes in the plane of the other film.

I. "Monte Carlo Simulations of Remanent Magnetization Decay Driven by Interactions," M. E. Matson, D. K. Lottis, and E. Dan Dahlberg, J. Appl. Phys. 75, 5475 (1994).

Many physical systems, including ferromagnets, exhibit slow relaxation behavior. In the case of ferromagnets, both the generation and decay of the magnetization upon the application and removal of an external field are quasilogarithmic in time (hence the term slow relaxation). The usual phenomenological model for this time dependence is to assume a distribution of energy barriers, where the relaxation over a given barrier follows a Debye relaxation law. A recently developed model based upon interactions replicates the slow relaxation phenomena without resorting to disorder [1]. This model, which has been applied to the magnetization relaxation in CoCr films [2] relies on a mean field approximation of magnetostatic interactions to be the driving force responsible for the decay. As a way to enhance our understanding of this type of relaxation, we have utilized an interacting Ising spin system simulating the dynamics using a Monte Carlo technique. It is found that this simulation faithfully reproduces the slow decay of the magnetization and the nonmonotonic temperature dependence of the decay slope with respect to temperature; both found in the original model. A comparison of the simulated decay with and without the interactions or couplings shows that, in fact, the slow relaxation is faster than that for a system without interactions. This of course merely reflects that the model system is being driven towards its equilibrium state by the interactions.

1. D. K. Lottis, R. M. White, and E. Dan Dahlberg, Phys. Rev. Lett. 67, 362 (1991).

J. "Ubiquitous non-exponential decay-The effect of long range couplings?," E. Dan Dahlberg, D.K. Lottis, R.M. White, M. Matson, and E. Engle (INVITED paper to MMM-Intermag- accepted for publication)

Many physical systems exhibit a dynamic response referred to either as slow relaxation, a quasilogarithmic time dependence, or a stretched exponential response. Historically this time dependence has been attributed to the presence of disorder which creates a distribution of relaxation times. In two papers,[1,2] we have shown that this time dependence can alternatively be explained to be a consequence of interactions or couplings. In the model, the interactions between relaxing spins, the dipole-dipole couplings, drive the system from an initial state towards equilibrium. As the system relaxes, the dipolar energy is reduced and the driving force diminishes. This process gives rise to the observed slow relaxation time dependence in a very natural manner. To guarantee the absence of disorder, the model considers the dipolar coupling or interaction between relaxing spins with a mean field approximation, the demagnetization field. Another feature observed in physical systems which the model explains is the nonmonotonic temperature dependence of the logarithmic

decay slope. In addition to a description of the model, measurements to determine the presence of interactions in some of the systems will be discussed.

1. D. K. Lottis, E. Dan Dahlberg, J. Christner, J. I. Lee, R. Peterson, and R. White, J. Appl. Phys. 63, 2920 (1988).
2. D. K. Lottis, R. M. White, and E. Dan Dahlberg, Phys. Rev. Lett. 67, 362 (1991).

K. "The effect of ion implant damage on the exchange coupling and magnetotransport in magnetic multilayers," M. Tondra, B. Miller, and E. Dan Dahlberg, to be submitted.

For the purpose of developing practical devices and as a mechanism to alter the giant magnetoresistance effect and the exchange coupling in magnetic multilayers, inert gas ions were implanted for controlled damage. With complete magnetic, structural, and magnetotransport measurements between increasing the ion doses, the systematics of many of the interesting phenomena occurring in magnetic multilayers has been investigated. Included in this study is the resistivity, the anisotropic magnetoresistance, the giant magnetoresistance, the Hall effect, the extraordinary Hall effect, the exchange coupling between the layers, the coercivity, and the value of the saturation magnetization.

L. "Accurate determination of the exchange coupling between Co and CoO," B. Miller, M. Tondra, and E. Dan Dahlberg, to be submitted.

The usual technique for determination of the antiferromagnetic/ferromagnetic (AF/F) exchange coupling is to measure the reverse coercivity of the pinned film. In this work, we found this measures only a lower limit for the pinning field. A more accurate measurement of the exchange coupling is measurements of the low field dependent small rotation of the pinned layer. Simply put, the reverse field coercivity measures a threshold a complex wall nucleation process, not the actual pinning. Our technique accurately determines the exchange and not the nucleation process. In addition, we have found an effective stiffness of the films by correlating a spiral length scale for a magnetization rotation as a function of the thickness of the films.

M. "Effect of the anisotropic magnetoresistance state on the measurement of the giant magnetoresistance: A critical testing of GMR models," B. Miller, M. Tondra, E. Chen, and E. Dan Dahlberg, to be submitted.

Accurate measurements of the giant magnetoresistance states in each of the two anisotropic magnetoresistance states allows a determination of the effect of a small change in the resistivity on the GMR. This provides a simple but controlled mechanism to alter the GMR in various systems. Using this data, we have been able to fit to models for the GMR. Being consistent with the models does not prove them, but does allow us to discard other models. In addition, the use of the models for interpretation of the data implies the interfacial scattering model GMR scattering must occur on a much shorter length scale than previously believed.

III. Invited Talks for Research Accomplishments

1. "Transport in Magnetic Multilayers," National Institute of Standards and Technology, Solid State seminar, Washington D.C., 21 Feb., 1992.

2. "Interfacial Scattering and the Giant Magnetoresistance Phenomenon," National Institute of Standards and Technology, Solid State seminar, Washington D.C., 18 June, 1992.

3. "What Anisotropic Magnetoresistance Tells Us About the Giant Magnetoresistance Phenomenon," NYU Physics Seminar, New York, NY, 26 June, 1992.

4. "Anisotropic Magnetoresistance in Multilayers: Something Old, Old, New, and New," Texas A&M Physics Department Seminar, College Station, Texas, 30 Nov., 1992.

5. "Transport in Magnetic Multilayers- Giant and Anisotropic Magnetoresistance," University of Texas at Austin Materials Science Seminar, Austin, Texas, 7 Dec., 1992.

6. "Giant Magnetoresistance: Where's the Scattering?," University of Texas at Arlington Physics Colloquium, Arlington, Texas, 8 December, 1992.

7. "Transport in Magnetic Multilayers: Something Old, Something New, Something Borrowed, Something I Blew!," University of Nebraska Solid State Physics Seminar, Lincoln, Nebraska, April, 1993.

8. "Anisotropic and Giant Magnetoresistance," ARPA/ONR Spin-Polarized Transport Workshop, Arlington, VA, 13-14 September, 1993.

9. "Transport in Magnetic Multilayers: Something Old, Something New, Something Borrowed, Something Blew!," University of Michigan Solid State Physics Seminar, Ann Arbor, Michigan, 5 October, 1993.

10. "Transport in Magnetic Multilayers: Something Old, Something New, Something Borrowed, Something Blew!," Michigan State University Solid State Seminar, East Lansing, Michigan, 13 December, 1993.

11. "Giant Magnetoresistance: Where's the Scattering?," General Motors Research Seminar, Detroit, Michigan, 14 December, 1993

12. "Slow Relaxation: An Effect of Interactions?," INVITED paper/talk to MMM-Intermag conference in Albuerquerue June, 1994.

13. "Transport in Magnetic Multilayers: Something Old, Something New, Something Borrowed, Something Blew!," Department of Materials Science Seminar, Iowa State Univesity, Ames, Iowa, 26 October, 1994.

IV. Personnel

A. Florczak,J.T., PhD in Physics received in 1992 (recipient of IBM predoctoral fellowship, 89-90) and currently employed at 3M Corp.
B. Chen, Y.-J., PhD in Physics received in 1992, currently employed by Motorola.
C. Tondra, M., Ph.D. Graduate Student in Physics (to graduate in August)
D. Miller, B., Ph.D. Graduate Student in Physics (to graduate in July).
E. Engle, E., Ph.D. Graduate Student in Physics (to graduate in July)
F. Kaufmann, D., Undergraduate Student in Physics, Graduated Summa Cum Laude, currently in the Carlson School of Management.
G. K. Sigsbee, K. Undergraduate Student in Physics, Graduated Summa Cum Laude, Currently in graduate school in physics at the University of Minnesota.
H. Sankar, S., Undergraduate Student in Physics, Graduated Summa Cum Laude, Currently in graduate school in physics at the University of California at San Diego
I. Jens Henrickson, Undergraduate Honors Student, , Graduated Summa Cum Laude, Currently in graduate school in physics at the University of Minnesota.
J. Dubravka Bilic, Undergraduate honors student in physics, graduated Summa Cum Laude, Currently in graduate school at the University of California, Berkeley.